Effect of Chitosan on Soil Stabilization

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RESUME Soil stabilization using biopolymers has emerged as an environmentally friendly alternative to traditional binders like cement and lime. In this study, Chitosan, a biopolymer derived from waste crustacean shells, was used to treat coarse and fine sand samples with various mass concentrations. We studied the hardness of the submerged samples in water for different periods, from one to six months, using cone penetration tests to evaluate the influence of Chitosan on soil stabilization. The results suggest that Chitosan-treated samples demonstrate increased hardness and can maintain their strength in the water for at least two months. Moreover, the durability in the water depends on the Chitosan concentration. The improved hardness of the samples is associated with the low moisture adsorption of Chitosan and its strong adhesion to sand particles. The findings provide valuable information to determine the optimal biopolymer concentration for future triaxial tests, which can further explore the shear strength parameters of Chitosan-treated soils.

Keywords: Soil stabilization, Chitosan, Sands, Cone penetration tests

I. INTRODUCTION

Biopolymer soil treatment (BPST) has become a popular topic in soil stabilization. Various biopolymers have been extensively studied in geotechnical engineering applications, such as Chitosan, Xanthan, Sodium Alginate, and Agar (Chang et al., 2020; Fatehi et al., 2021; Huang et al., 2021; Idoui et al., 2022). These biopolymers are naturally derived and environmentally friendly. Among them, Chitosan exhibits several unique properties, such as non-toxicity, bacteriostatic behavior, biodegradability, and a polycationic nature, making it suitable for industrial, medical, pharmaceutical, and environmental applications (Adamczuk and Jozefaciuk, 2022; Mussabayeva et al., 2022). Moreover, Chitosan is derived from chitin, which is usually obtained from processed discarded crab and shrimp wastes (Aguilar et al., 2016). Compared to traditional stabilizers like cement or lime, biopolymer treatment offers potential benefits in terms of lower carbon footprint and reduced resource depletion (Fatehi et al., 2021). Considering these advantages, this study employs Chitosan as a biopolymer to treat coarse and fine sands.

Recent research has demonstrated the effectiveness of Chitosan in soil stabilization. However, most studies have primarily focused on dry soils. For instance, Shariatmadari et al.(2020) reported that the unconfined compressive strength (UCS) of treated sandy soils increases with Chitosan concentration but decreases over time. Similarly, Azimi et al. (2024) investigated the effect of different Chitosan concentrations and curing times on the UCS of high-plasticity clayey soil. They observed that UCS increased with Chitosan concentration up to an optimum dosage of 1.5%, after which it is reduced. Moreover, extending the curing time from 7 to 28 days further enhanced UCS at a given concentration.

Some studies have also investigated wet soil samples. Hataf et al. (2018) conducted UCS tests on treated clayey soil under optimal conditions and found that the UCS increased with Chitosan concentration during the early curing stages (1, 3, and 7 days). However, after 28 days, the UCS decreased to the level of untreated specimens when the Chitosan concentration exceeded 0.16%. Similarly, Amiri Tasuji et al. (2024) explored the impact of Chitosan concentration and curing time on the mechanical strength of sandy soils, reporting a continuous increase in UCS with concentration and curing time.

While these studies demonstrated the potential of Chitosan in soil stabilization, they often focused on dry or wet samples that do not fully represent real-world conditions. Additionally, the relationship between Chitosan concentration and soil strength is not always very clear.

To address these limitations, this study aims to provide a fundamental investigation into Chitosan's performance in soil stabilization. The research focuses on two key aspects:

1. Conducting cone penetration tests to evaluate the evolution of the strength of saturated specimens over time;
2. Optimizing Chitosan concentration: Different concentrations of Chitosan solutions are used to treat coarse and fine sands, identifying the optimal dosage;

II. Methodology

A. Materials and Preparation

Coarse and fine sands used in this study were extracted by sieving from the Arve River in the French Alps. These sands are predominantly composed of pure quartz. The grain size distributions of the two sands are shown in Figure 1.

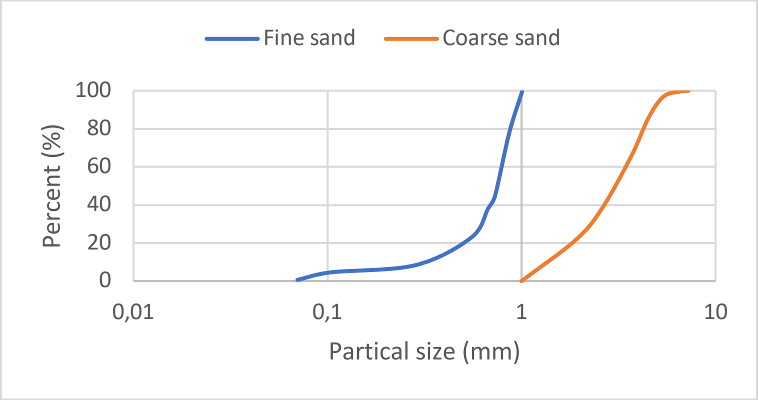


FIGURE 1. **Particle size distribution of coarse and fine sands**

Chitosan, derived from chitin, is produced from the waste of crustacean shells, such as shells of crabs and shrimps. It is a linear polysaccharide, and the main components of chitosan are β-1,4-D-glucosamine ($C_6H_{13}NO_5$) and N-acetylglucosamine ($C_8H_{15}NO_6$) (Amiri Tasuji et al., 2024).

Two standard mixing methods are commonly employed for specimen preparation: dry mixing and wet mixing. The dry mixing method involves first mixing the dry biopolymer powder with dry soil, followed by the addition of water. This allows the biopolymer to form a gel structure during the curing process. In contrast, the wet mixing method involves forming the gel first by dissolving the biopolymer powder in water and then mixing it with the dry soil. The dry mixing method ensures uniform distribution of the biopolymer before hydration and is more practical for field applications, but it may lead to inconsistent gel formation. The wet mixing method allows for the complete dissolution of the biopolymer, leading to better bonding, especially in fine sands, but it is more time-consuming and harder to handle due to the gel's viscosity.

In this paper, the wet mixing method was selected because Chitosan is soluble only in solutions with a pH below 6.5 and has a tendency to bind to negatively charged surfaces (Kavazanjian et al., 2009). To prepare the specimens, Chitosan powder was dissolved in a 1% acetic acid solution. The dissolution process involved manual mixing with a stainless steel spoon until the mixture became uniform, typically requiring about 15 minutes. A visual inspection was conducted to ensure the gel was homogeneous and free from undissolved particles or air bubbles.

The prepared biopolymer gels were then mixed with dry soil and compacted into small plate molds (diameter: 53mm; height: 13 mm). The specimens were cured at room temperature for 7 days. Figure 2 illustrates examples of the prepared plate samples.

FIGURE 2. Specimens for cone penetration tests

The biopolymer's concentration (m_b) is calculated by the ratio of biopolymer mass to dry soil mass (Eq.1), while the initial water content (m_w) is the ratio of water mass to dry soil mass (Eq.2):

$$m_b = \frac{\text{mass of biopolymer}}{\text{mass of dry soil}} \tag{1}$$

$$m_w = \frac{\text{mass of water}}{\text{mass of dry soil}} \tag{2}$$

Chitosan solutions with varying concentrations were prepared to treat both coarse and fine sands. Table 1 summarizes the conditions for the Chitosan-treated specimens used in cone penetration tests.

TABLE 1. **The conditions of Chitosan-treated specimens**

Name	m_b	m_w
Ch-CS-1	1%	8.5%
Ch-CS-2	2%	10.4%
Ch-CS-3	3%	17.6%
Ch-CS-4	4%	18.5%
Ch-CS-5	5%	19.7%
Ch-FS-1	1%	10.3%
Ch-FS-2	2%	12.8%
Ch-FS-3	3%	19.6%

Note: (In the table, Ch means chitosan; CS and FS mean coarse and fine sands, respectively; the number of the name infers the m_b%)

B. Tests

Dynamic vapor sorption (DVS) test

The DVS Intrinsic device used in this study is from Surface Measurement Systems (SMS) Co.; it is controlled by the DVS-WIN software package supplied with the instrument, which allows the conduct of sorption and desorption experiments under controlled temperature and relative humidity conditions. Each DVS test lasted about 2 weeks for samples of approximately 70-100 mg. The procedure is as follows:

1. Set the experimental conditions, including temperature (25°C) and relative humidity range (10%-95%)
2. Expose the biopolymer to controlled step-by-step changes in humidity.
3. Measure the resulting changes in Chitosan mass to determine its moisture adsorption properties.

Cone penetration test

To evaluate the effectiveness of chitosan in stabilizing sandy soils, cone penetration tests were conducted following the NF EN ISO 17892-12 standard. The test utilizes a penetrometer with a cone-shaped tip, typically used to determine the liquid limit of clayey soils (Figure 3). Figure 4 shows the relationship between shear yield stress and penetration depth. In this study, penetration depth was measured to assess the hardness and softening behavior of chitosan-treated sand specimens. The cone, with a mass of 100 g, an apex angle of 10 degrees, and a base diameter of 10 mm, was allowed to penetrate the soil under its own weight. The depth of penetration was then recorded to evaluate the changes in soil resistance over time. The procedure of the test is as follows:

1. Put the initially dry specimen under the cone, ensuring full contact; press the button and apply a controlled weight to allow penetration, then record the depth.
2. Repeat the above steps and test other points on the surface of this sample. Normally, for each sample, at least three points were tested in the central part, intermediate region, and edge part. Calculate the mean value based on the three tests.
3. Submerge the sample into water for several days, weeks, or months, and repeat the tests as indicated above.

FIGURE 3. **Cone Penetration Test**

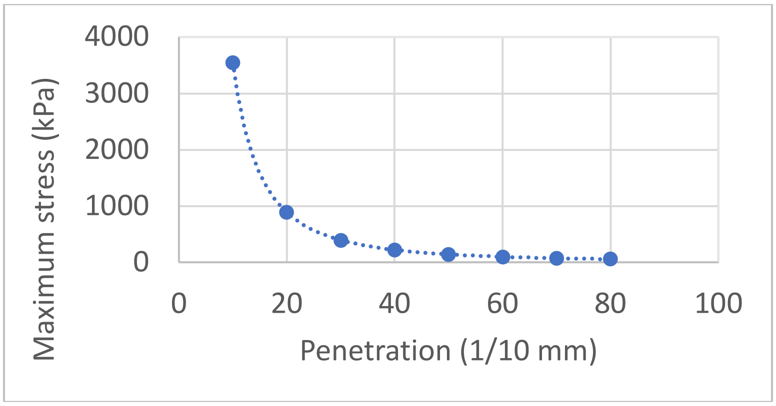


FIGURE 4. **Shear yield stress-penetration curve**

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM, from ZEISS) was employed to characterize the morphology of the samples in order to analyze the interaction between sand particles and chitosan. Two groups of samples were selected for the SEM characterizations: untreated fine sand and fine sand treated with 1% Chitosan. In order to keep the original morphology of the samples, the samples were dried by freeze-drying.

III Results

DVS results

The DVS isotherm plot of Chitosan is shown in Figure 5. The mass of Chitosan increased steadily as the target relative humidity (RH) rose. When the RH reached 95%, the mass change was approximately 22%. This relatively low sorption and desorption observed in the Chitosan curves at high RH levels suggests that Chitosan exhibits low sensitivity to water. Furthermore, these results further validated the fact that Chitosan is insoluble in water.

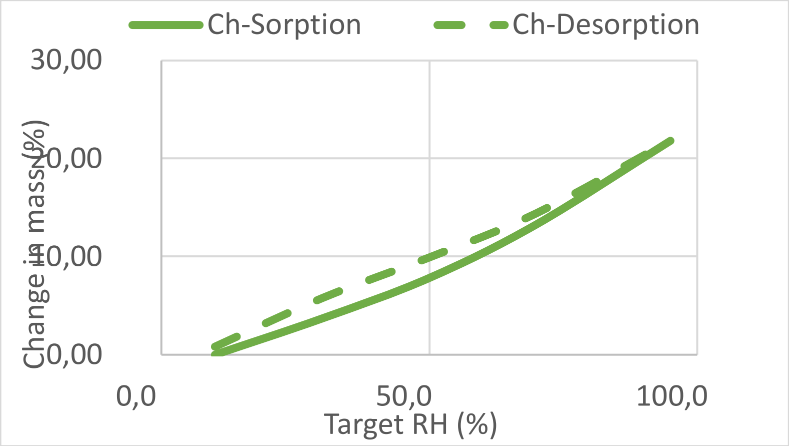


FIGURE 5. **DVS isotherm plot of Chitosan (in the label: Ch is Chitosan)**

Results of Cone penetration tests

In the cone penetration tests, a specimen was considered completely soft when the penetration depth exceeded 10 mm, indicating a significant loss of structural integrity. The depth penetration in the dry specimen was normalized to 0 mm because the dry sample was hard enough to resist penetration. This was confirmed through testing, where no measurable penetration was observed. Given that the total specimen height was 13 mm, this normalization provided a clear reference point for evaluating the softening behavior of the treated samples.

Figures 6 and 7 illustrate the evolution of penetration depth over time for Chitosan-treated coarse and fine sands under submerged conditions.

For coarse sand, during the initial two months, all treated coarse sand specimens remained hard, with penetration depths below 1.5 mm. After 60 days, some samples began to soften: Ch-CS-1 showed the most significant increase in penetration depth, particularly after 120 days, eventually exceeding 8 mm. Ch-CS-2 exhibited smaller increases in penetration depth during the same period. Ch-CS-3 remained hard for the whole six-month period, only with a very small penetration depth below 0.6 mm at 160 days. Ch-CS-4 and Ch-CS-5 remained hard throughout the six-month period, maintaining penetration depths of 0 mm.

The behavior of fine sand specimens followed a similar trend. During the first two months, all treated samples remained hard, with penetration depths below 1.2 mm. After 60 days, Ch-FS-1 exhibited the most significant increase, reaching a penetration depth of 11 mm after 160 days. Ch-FS-2 and Ch-FS-3 remained stable, showing minimal changes over the six-month period. It is evident that Ch-FS-2 exhibits a lower penetration depth compared to Ch-CS-2 despite having the same chitosan content. This may be attributed to the smaller grain size of fine sand, which enables chitosan to form more effective bonds between particles, resulting in a stronger and more cohesive structure that reduces penetration depth. Additionally, the lower porosity of fine sand allows chitosan to better bridge the gaps between particles, creating a denser and more resistant matrix.

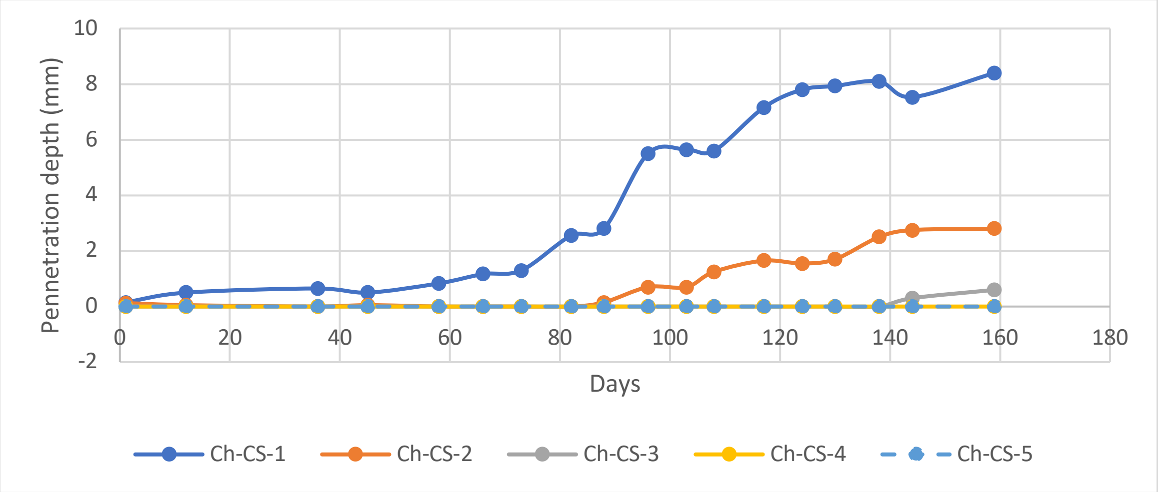


FIGURE 6. **Penetration depth evolution of Chitosan-treated coarse sand under submerged conditions**

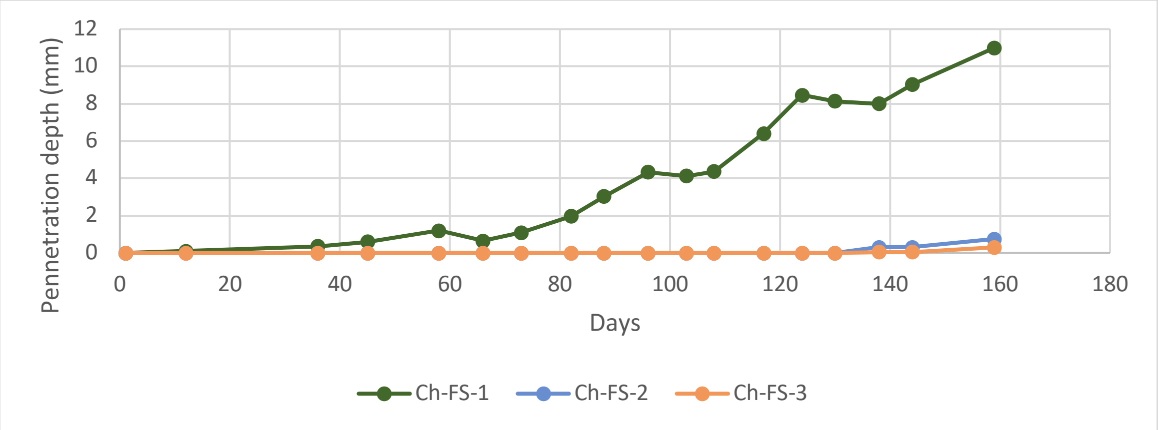


FIGURE 7. **Penetration depth evolution of Chitosan-treated fine sand under submerged conditions**

SEM

These findings indicate that Chitosan concentration significantly influences the long-term performance of the treated specimens under submerged conditions. For both coarse and fine sands, a 1% Chitosan content was sufficient to stabilize the soil effectively. Given that Chitosan is relatively expensive, with a market price of approximately 220 euros per kilogram, using higher concentrations may not be economically feasible for large-scale applications. From both performance and economic perspectives, 1% Chitosan appears to be the optimal choice for further investigations, such as consolidated drained triaxial tests.

In addition, it can also be found that the performance of fine sand is better than that of coarse sand. Hence, to study the mechanism of stabilization and interaction between Chitosan and fine sand particles, SEM will be used to observe the micro-morphology in the specimens.

The SEM images for untreated fine sand and 1% Chitosan-treated fine sand are presented in Figure 8 and Figure 9, respectively. First, as indicated by Figure 7, the surface of the fine sand is rough, with no obvious binding materials between particles. However, in Figures 9 (a) and (b), the Chitosan wires can be observed on individual sand grains and bridging between adjacent particles. These Chitosan wires adhere strongly to the sand, enhancing the hardness of submerged specimens. The strong adhesion observed in SEM images is primarily attributed to a combination of electrostatic attraction and hydrogen bonding, further reinforced by the gel-like network formed by hydrated chitosan. These interactions significantly improved the mechanical properties and water resistance of chitosan-treated sand.

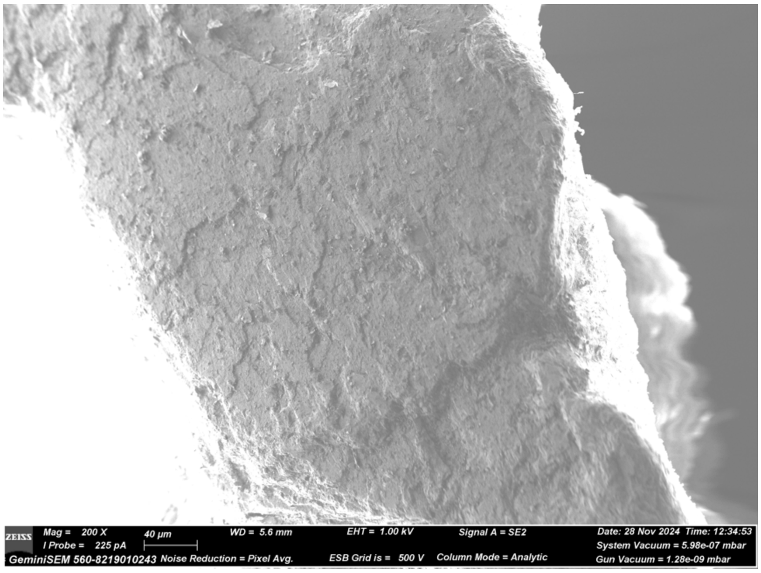
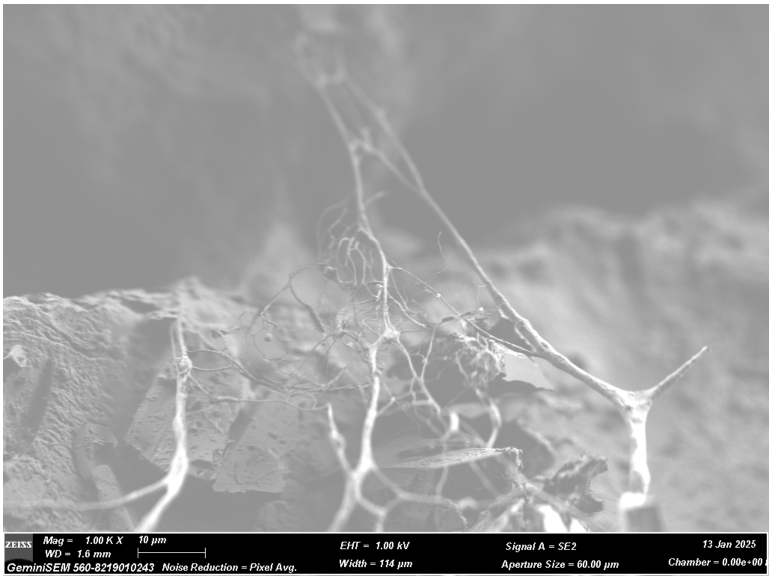
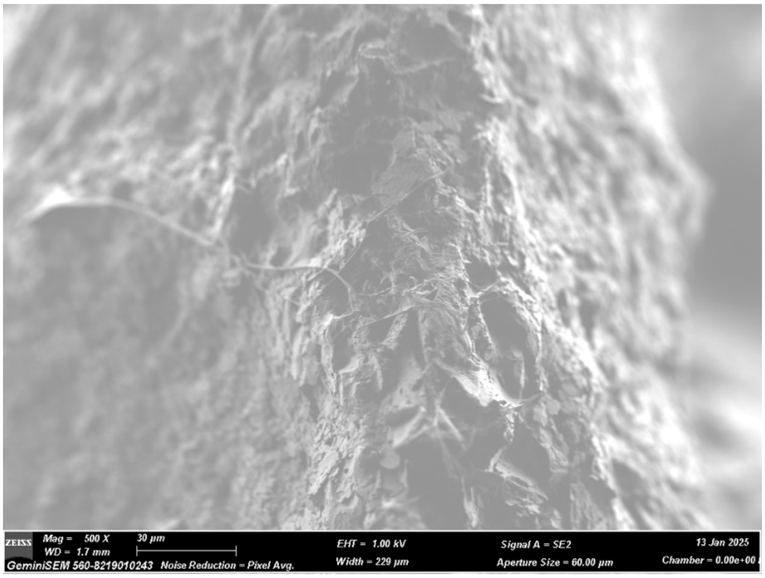


FIGURE 8. **SEM photos of untreated fine sand**



(a) Gels connecting soil particles



(b) Gels connecting soil particles

FIGURE 9. SEM photos of Chitosan-treated fine sand (Ch-FS-1)

Ⅳ Conclusions

This paper presents a preliminary study to evaluate the effectiveness of Chitosan in stabilizing coarse and fine sands under submerged conditions. The results of DVS highlighted Chitosan's low moisture adsorption, indicating its potential application in saturated environments. Cone penetration tests showed that treated soils maintained strength for extended periods, with higher Chitosan concentrations (more than 2%) enhancing long-term stability. However, a 1% Chitosan concentration appeared to be optimal for both coarse and fine sands. SEM analysis confirmed that

Chitosan forms gels that bind and coat soil particles by a wired network, improving the mechanical properties of the materials.

This research serves as a preliminary study to understand the behavior of Chitosan-stabilized soils. Future work will build on these results, using consolidated drained (CD) triaxial tests for a more comprehensive evaluation of the soil performance under different confining pressures.

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